CFD based design and optimisation of wood log fired stoves

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ABSTRACT: The optimised design of wood log fired stoves with regard to CO emissions, fine particulate emissions from incomplete combustion and efficiency is necessary due to decreasing emission limits and due to market demands. Thus, there is a need to apply modern simulation techniques such as Computational Fluid Dynamics (CFD), which are increasingly being used as efficient tools for plant design. While CFD is successfully being applied for the simulation and analysis of turbulent reactive flows in the combustion chamber of biomass grate furnaces, no models for the combustion of wood logs in stoves were available up to now due to the highly transient and interlinked complex processes occurring in such devices. Therefore, BIOS has developed an innovative CFD based model for wood log fired stoves operated in batch mode consisting of an empirical model for wood log combustion and CFD models for the turbulent, reacting flow and heat transfer in the stove. After validation, the model was applied for the CFD aided design of a new wood log fired stove of the Austrian stove manufacturer HAAS+SOHN Ofentechnik GmbH. The CFD aided design of the stove led to considerably reduced CO emissions and fine particulate emissions with an efficiency of the stove > 80%. Moreover, the simulation results showed that the model represents an efficient analysis and design tool.
Keywords: alternative energy, biomass, modelling, stove, wood.

1 INTRODUCTION AND GOALS

While CFD simulations of reactive flow in the combustion chamber are successfully being performed for biomass fixed bed and grate furnaces of all scales ([2][3][4][5][6][7]), no CFD models for the combustion of wood logs in small-scale stoves were available up to now due to the high complexity of the transient processes occurring in such devices.

Therefore, BIOS has developed and validated a CFD based model for wood log fired stoves. This model consist of an empirical model for wood log combustion and CFD models for the turbulent reactive flow and heat transfer processes in the stove. The model was applied for the CFD aided design of a new wood log fired stove of the Austrian stove manufacturer HAAS+SOHN Ofentechnik GmbH. The model was employed to study the flow of combustion air, convective air in the double jacket and flue gas (FG) in the combustion chamber, gas phase combustion, as well as heat transfer processes (conduction, convection and radiation) between gas phase, stove materials (lining, metal sheets and glass window) and the surroundings. The simulation results served as a basis for an improved design and control of the stove concerning mixing of flue gas with air, utilisation of the combustion chamber, flue gas burnout, reduced CO emission and fine particulate emissions from incomplete combustion, as well as concerning an increased thermal efficiency by lowered excess air and a higher thermal output of the stove.

First, the basic concept of the stove was evaluated with the model developed. In the next step, a parameter study with regard to the geometry of the stove and air staging was performed. The final geometry, as outcome of the parameter study, was realised as prototype. Test runs were performed for this prototype in several batches. CFD simulations of the stove were performed for selected operating conditions. Based on the outcomes of the test runs and the CFD simulations, final adaptations of the stove geometry were performed and a basic concept for the process control of the stove was derived.

2 METHODOLOGY

As already explained, a model for the CFD analysis of wood log fired stoves has been developed. The model development and check, as well as the design and optimisation of the stove took place in several steps.

Results from test runs with testing stoves from HAAS+SOHN Ofentechnik GmbH served as a basis for model development and validation.

The basic concept of the 8 kW natural convection wood log stove (see Figure 1 and 2) was evaluated for two steady-state operating cases (basic 1 and basic 2, see Table I) defined based on the test run data with the testing stoves.

In the next step, a parameter study with regard to the geometry of the stove including the air supply was done for one selected operating case (basic 1, see Table I), and for the best case geometry additionally concerning air staging by reducing excess air (case pre-opt 1, see Table I). The pre-optimised geometry together with additional secondary air nozzles was realised as prototype. Test runs were performed for this prototype in a series of batches. CFD simulations were performed for two steady-state operating cases defined for one selected batch (case opt 1, case opt 2, see Table I), whereas model parameters and release profiles of the empirical wood log combustion model were adjusted to the test run results. The model was checked a second time and finally evaluated by a comparison with measurements of flue gas temperatures in different plant zones and CO emissions of stove outlet.

2.1 Investigated stove geometries and model overview

In the following, the stove and models for relevant processes are explained by means of a scheme (see Figure 1) of the optimised variant of the stove (see Figure 2), which was realised as prototype.

The simulation of wood log combustion and the CFD simulation of turbulent reactive flow and heat transfer in the combustion chamber were performed in a 2-step approach. The wood logs are represented as volumes (bright green region), whereas the volatiles are released from an outer layer (dark green region) defined as porous zone. The bed of embers (black region), where char burnout takes place, is also modelled as porous zone.

For the operating cases considered, the release of volatiles from the wood logs and the bed of embers is calculated by an in-house developed empirical wood log combustion model which constitutes an enhancement of an empirical model for fixed bed combustion (see section 2.2 and section 2.3).

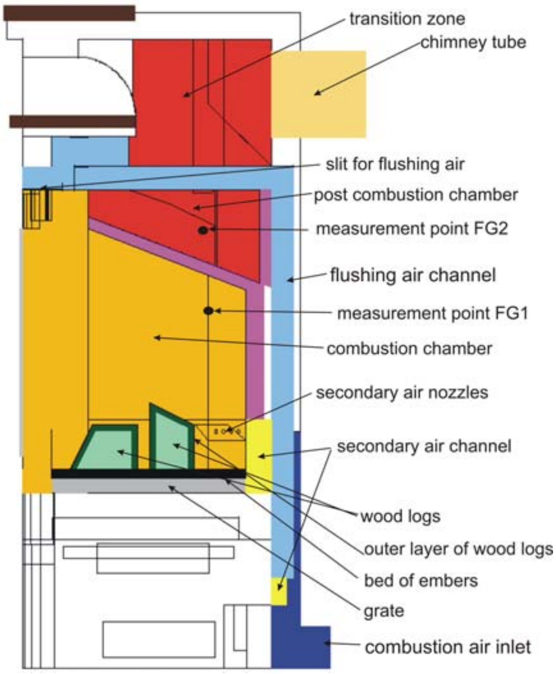

Figure 1: Geometry of the optimised variant of the wood log fired stove

The CFD simulation domain of the stove starts with the combustion air inlet (dark blue region), which separates into two channels, one for the air that flushes the glass window (bright blue region) and, only for the optimised variant, one additional channel for the secondary air (yellow region), which is injected from the backside of the combustion chamber and deflected by a metal sheet, such that the secondary air does not directly hit the wood logs. The combustion chamber (orange region), the post-combustion chamber (lower red region) and the transition zone to the chimney tube (upper red region) are also displayed. The stove materials which are lining (magenta region), stones (brown region), steel and glass sheets (see Figure 2 left), as well as the double jacket for air convection, which contains several orifices for the air (see Figure 2 right) are also contained in the computation domain. The ash tray at the bottom of the stove was not included.

Flow and gas phase combustion simulations were performed using the Realizable k-ε Turbulence Model, the Eddy Dissipation / Finite Rates Kinetics Combustion Model [1] in combination with a global methane 3-step mechanism (CH_4, CO, CO_2, H_2, H_2O and O_2 considered) which was extended for the wood log combustion model by a an additional reaction step and species (volatiles), respectively (see section 2.3 and Figure 4), and the Discrete Ordinates Radiation Model. The CFD sub-models were validated by lab-scale test cases ([see [3], [7]). The overall CFD model for biomass fixed bed furnaces (in combination with the basic empirical fixed bed combustion model; see section 2.2) was validated with test runs for several biomass fixed bed and grate furnaces (see e.g. [7]). Within this work, the CFD based model for wood log fired stoves, which constitutes an enhancement of the overall model for biomass fixed bed furnaces, was checked by a comparison with measurements during several test runs.

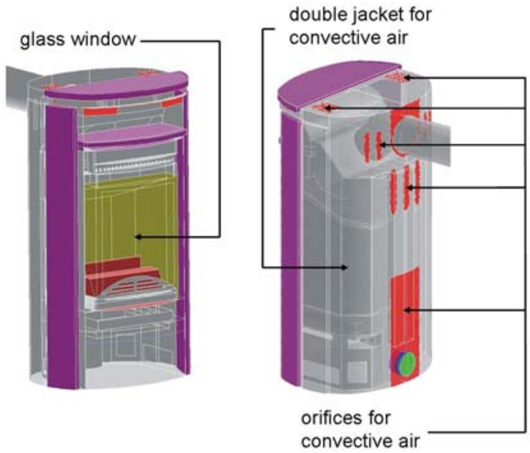

Figure 2: Geometry of the wood log fired stove

2.2 Basic empirical fixed bed combustion model

An empirical model was developed for the combustion of solid biomass in fixed beds. The results (mass and energy fluxes from the fuel bed to the gas phase) are used as boundary conditions for subsequent CFD simulation. The model consists mainly of three parts (for a more detailed description see [2] [3] [4] [7]).

- One-dimensional profiles along the grate, which describe the degradation of the fuel components C, H and O, as well as fuel drying, were defined based on assumptions and experimental data (see [7]).
- Conversion parameters, which describe the formation of the most important flue gas components for combustion simulation (CH_4, CO, CO_2, H_2, H_2O and O_2) are defined based on assumptions, as well as experimental and literature data ([3], [7]).
- The two steps above enable a discrete balancing of mass and energy fluxes released from the fuel bed along the grate.

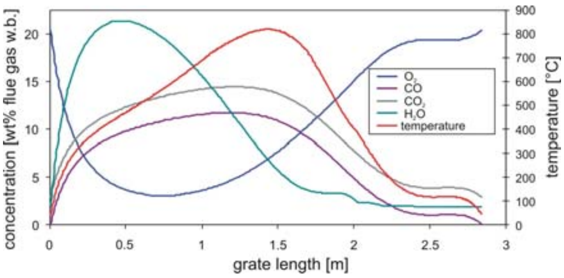

Figure 3: Basic fixed bed combustion model: examples for species and temperature profiles along the grate

2.3 Adaptation of fixed bed combustion model for wood log combustion and derivation of operating data

Volatiles release model: In order to model the combustion of wood logs and volatiles release as boundary conditions for CFD simulations (source terms), the fuel was divided into three fuel components (see Figure 4): water vapour, volatiles ($C_xH_yO_z$, a pseudo-component representing all hydrocarbon species released) and char (22.5 wt% d.b. of fuel assumed, based on internal data from TGA experiments). The volatiles are assumed to further react to the intermediates CH_4, CO, CO_2, H_2 and H_2O, whereas the split into the single components was estimated with thermodynamic calculations under the assumption of equilibrium in the gas phase at 800 °C. In the gas phase, these intermediates finally react to the products CO_2 and H_2O (reactions are considered in the CFD simulations).

Assuming heterogeneous Boudouard equilibrium at temperatures above 800 °C, char is converted into CO (reactions considered in the release model), which further reacts to CO_2. A scheme of reactions considered, as well as of the release model for wood logs is shown in Figure 4.

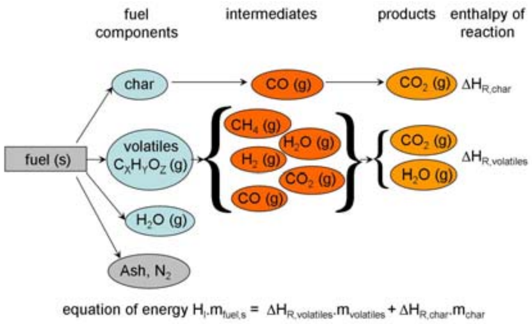

Figure 4: Scheme of reactions considered and model for the release of volatiles during wood log combustion; solid fuel components considered: volatiles ($C_xH_yO_z$), vapour from drying (H_2O) and char; N-species were released as N_2; release rates are source terms in the CFD simulations

Derivation of time-dependent release profiles: In order to simulate the unsteady combustion of wood logs in a batch process, the empirical fixed bed combustion model (see Figure 3) was modified based on data from test runs with wood log fired stoves. The basic model was adapted in order to derive time-dependent profiles of wood log combustion by transferring the profiles along the grate into a time-dependent profile. Here, the release profiles were modified in order to fit calculated O_2 concentrations at stove outlet with measurement values (see Figure 5).

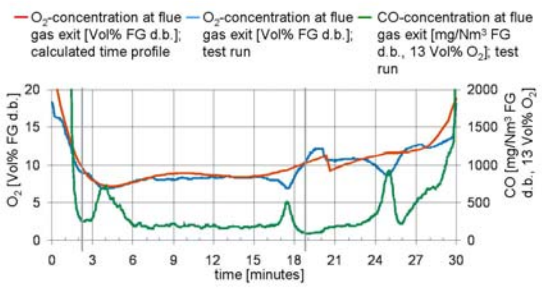

Figure 5: O_2 concentrations as a function of time measured in the chimney during test runs (blue curve) in comparison with the calculated O_2 concentrations (red curve), as well as measured CO emissions (green curve); (FG = flue gas)

Using the defined time-dependent release profiles, the composition of a virtual fuel with the components C, H, O and water vapour, which are released during fuel decomposition (see Figure 6 and Table I) can be determined at any time. In combination with time-dependent combustion air mass flows (based on measurements and assumptions), mass and energy fluxes, as well as operating conditions can be determined at any given time during a combustion batch.

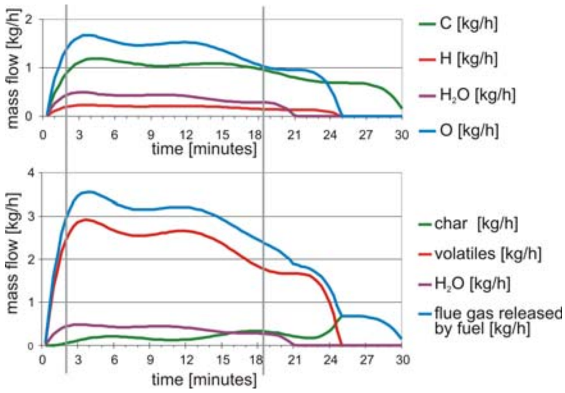

Figure 6: Time-dependent mass flux of fuel components and division into water, volatiles and char (bottom), as well as division into C, H, O and water vapour

An energy balance over the stove was performed based on test run data (see Figure 7). The energy balances allow the definition of two operating cases, as a basis for the steady-state simulations, where the heat storage of the stove is approximately zero. The heat storage is calculated as the difference of fuel power related to NCV and the sum of heat fluxes over the surface of the stove (thermal output) and exhaust gas losses. The time-dependent fuel power related to NCV is calculated with the virtual fuel defined by the release profiles, the time-dependent thermal output over the surfaces is estimated based on surface temperature measurements and additional CFD simulations and the time-dependent exhaust gas losses are estimated by temperature measurements in the chimney and CFD simulations.

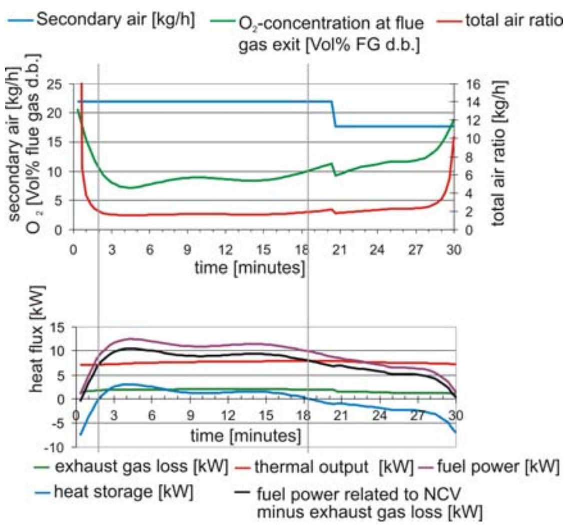

Figure 7: Time-dependent profiles of combustion air mass flux, oxygen concentration and heat fluxes

Table I: Operating conditions: fuel composition, calorific values, mass fluxes, total air ratio and oxygen concentration at flue gas outlet

Load case		basic 1	pre-opt 1	opt 1
Parameter	Unit			
Water	[wt% w.b. ash-free]	14.1	14.1	15.0
C	[wt% d.b. ash-free]	39.0	39.0	36.0
H	[wt% d.b. ash-free]	7.7	7.7	7.8
O	[wt% d.b. ash-free]	53.1	53.1	56.0
N	[wt% d.b. ash-free]	0.2	0.2	0.2
Gross calorific value (GCV)	[MJ/kg d.b.]	17.1	17.1	15.7
Net calorific value (NCV)	[MJ/kg w.b.]	12.9	12.9	11.6
Fuel power related to NCV	[kW]	12.6	12.6	9.5
Flue gas in combustion chamber - total	[kg/h]	37.0	31.2	25.0
Flue gas released from fuel	[kg/h]	3.5	3.5	2.9
mass flow of air	[kg/h]	33.5	27.7	22.1
Total air ratio	[ ]	2.3	1.9	2.0
O_2 concentration at stove outlet	[vol% d.b.]	11.9	10.0	10.6
Fuel mass flow	[kg w.b./h]	3.5	3.5	2.9

3 RESULTS AND DISCUSSION

3.1 Model check

The basic CFD model for biomass fixed bed furnaces was validated and checked for different biomass combustion plants (see [3], [4], [5], [7]). In this work, the model was adapted for wood log combustion and checked for wood log fired stoves by a comparison with measurements during different test runs with 8 kW wood log stoves of the company HAAS+SOHN Ofentechnik.

During a first set of test runs with the basic geometry, surface temperatures of the double air jacket at various positions (O1 – O6), one convective air temperature (L2), one combustion air temperature (L1) and one flue gas temperature after the stove were measured (see Figure 8, where O denotes positions of surface measurement points and L denotes positions of measurement points for air; the flue gas measurement point is not shown – it was positioned in the chimney tube 500 mm after stove outlet).

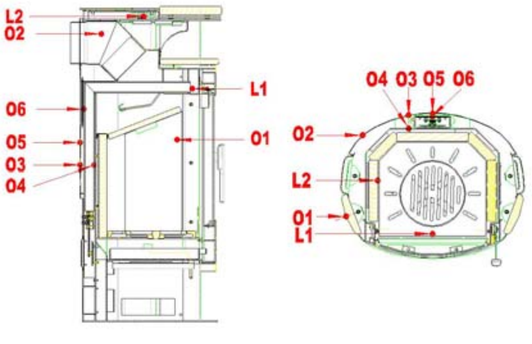

Figure 8: Measurement points of surface temperature (O) and air temperature (L) of the basic geometry
Explanations: flue gas temperature measurement position in the chimney 500 mm after the stove is not shown here

Using the shell conduction model for heat transport in metal sheets, CFD simulations resulted in a realistic and smooth distribution of the surface temperature (see Figure 9). For all validation cases (two stoves with two operating cases per stove; only results for one stove are shown here) the simulations lead to surface temperatures, which, generally, are in good agreement with measurements (with the exception of O6 with larger measurement uncertainties), as can be seen in Table II.

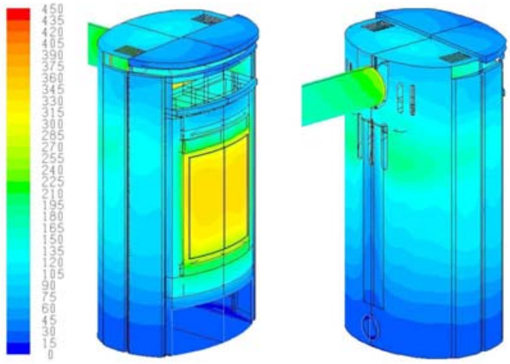

Figure 9: Iso-surfaces of the outer surface-temperatures [°C] of the basic geometry; 3D view of the stove from front (left) and back (right)

Moreover, for these operating cases, the simulated values of air and flue gas temperature are in good agreement with thermocouple measurements, which were corrected with an energy balance model in order to consider the influence of radiation (see tables II).

Also thermocouple measurements of flue gas temperature in the combustion chamber, in the post-combustion chamber and in the chimney after the stove during test runs with the optimised stove, showed a good agreement between simulations and measurements (see Table III).

Moreover, a comparison of simulated and measured CO emissions was performed for the optimised geometry and the operating cases opt 1 and opt 2. Here, it should be noted, that the measured values of the CO emissions vary heavily during the duration of a batch (see green curve in Figure 5). Considering this problem and the complexity of wood log combustion in a stove, it can be stated that the predicted CO emissions are in reasonable agreement with the measurements (see Table III).

Table II: Comparison of measured and simulated surface temperatures, air temperatures and flue gas temperatures for the basic geometry of the stove, operating point basic 1 and basic 2

Load case		basic 1		basic 2	
Parameter	**Unit**	**Simulation**	**Measurement**	**Simulation**	**Measurement**
Surface temperature O1	[°C]	100	123	96	125
Surface temperature O2	[°C]	82	110	81	115
Surface temperature O3	[°C]	105	104	105	103
Surface temperature O4	[°C]	272	277	273	283
Surface temperature O5	[°C]	101	103	99	104
Surface temperature O6	[°C]	230	152	222	159
Temperature at measurement point L1 - secondary air	[°C]	201	202	184	227
Temperature at measurement point L2 of convective air at the exit of the double jacket	[°C]	109	149	115	160
Flue gas temperature 500 mm after stove outlet	[°C]	328	325	339	339

Table III: Comparison of measured and simulated CO emissions and flue gas temperatures for the optimised geometry of the stove (prototype version) for load cases opt 1 and opt 2; see Figure 1 for the position of FG1 and FG2; measurement point in chimney tube according to EN13240

Load case		opt 1		opt 2	
Parameter	**Unit**	**Simulation**	**Measurement**	**Simulation**	**Measurement**
CO emissions measured in the chimney tube	[mg/Nm3 FG d.b., 13 Vol% O2]	270	316	235	124
Flue gas temperature measure in the chimney tube	[°C]	268	240	272	265
Flue gas temperature at point FG1 in the combustion chamber	[°C]	820	648	868	844
Flue gas temperature at point FG2 in the post combustion chamber	[°C]	589	537	604	928

Summing up, the simulation results showed that the measurements of CO emissions, air and flue gas temperatures, as well as surface temperatures could be qualitatively and satisfactorily reproduced. This leads to the conclusion, that also the underlying processes of flow, gas phase combustion and heat transfer can be predicted with reasonable accuracy with the newly developed model. Thus, this model can be utilised as an efficient analysis and design tool for wood log fired stoves.

3.2 Design study

The CFD analysis of the basic geometry of the stove investigated (as conveyed by the company), revealed a rather large volume in the rear part of the main combustion chamber with low oxygen concentrations (see Figure 12), as well as bypass flows in the post combustion chamber (see Figure 10). Furthermore, the temperatures of the flue gas in the burnout zone were rather low (see Figure 11) which led to high CO emissions (see Figure 13). Moreover, excess air was high due to a poor mixing of unburned flue gas with air, and heat transfer to the surroundings was low due to the relatively small heating surface of the transition between the post-combustion chamber and the chimney, which is not lined. Together, both effects lead to a rather low efficiency and increased emissions of the stove.

During the parameter study various variations of the stove geometry were investigated in order to optimise the utilisation of the combustion volume of the combustion chamber, to improve turbulent mixing, to elevate flue gas temperatures in the burnout region of the stove, and finally to improve flue gas burnout and to increase the thermal output (the efficiency) of the stove.

The best case variant, which constitutes a considerable improvement compared to the basic geometry, concerning flue gas burnout and thermal efficiency (results see Figure 10 to Figure 13), had an additional lining of the post-combustion chamber to increase flue gas temperatures, as well as a modified design of the deflection in the post-combustion chamber to avoid bypass flows and to improve mixing of flue gas with air at sufficiently high temperatures in order to achieve an efficient flue gas burnout with low CO emissions and low fine particulate emissions from incomplete combustion. Furthermore, the transition zone between post-combustion chamber and chimney, which is not insulated, was considerably enlarged and a deflection sheet was installed in the transition zone in order to increase heat transfer and thermal efficiency of the stove. The simulations also showed, that additional orifices in the double jacket for convective air did not significantly increase the thermal output of the stove in the present case. Moreover, excess air was reduced during the main combustion phase (target value total air ratio ≤ 2.0) in order to increase the flue gas temperatures as a basis for a more efficient flue gas burnout and to increase the efficiency of the stove.

Additional to the modifications of the pre-optimised geometry, secondary air nozzles were installed in the rear wall of the combustion chamber in order to inject combustion air in the large zone with low oxygen concentrations (see Figure 10 and Figure 12) to achieve a better exploitation of the combustion chamber at elevated flue gas temperatures (see Figure 11) and to improve flue gas burnout (Figure 13). This optimised variant, as a result of the parameter study, was realised as a prototype. Test runs were performed with this prototype in a series of batches. Moreover, CFD simulations were done for operating conditions derived from selected test runs.

When comparing simulation results for the basic and optimised geometry, the CO emissions could be considerably reduced from 458 mg/Nm^3 (dry flue gas, 13 vol% O_2), to 270 mg/Nm^3. Moreover, the total air ratio was reduced from 2.3 to 2.0 and the thermal efficiency was increased from 69% to 81% for the operating case considered. As a next step, final adjustments of the stove geometry were performed and a new process control concept was derived based on the test runs. The optimised stove was realised as new prototype. Test runs confirmed the low CO, OGC and particulate emissions, as well as a high efficiency of the stove > 80% (see Table IV).

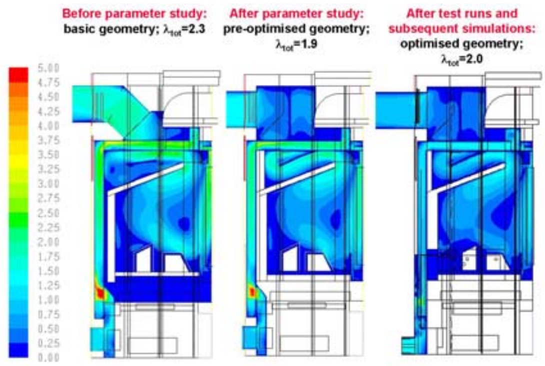

Figure 10: Selected results: iso-surfaces of air and flue gas velocity [m/s] in the vertical symmetry plane of the stove

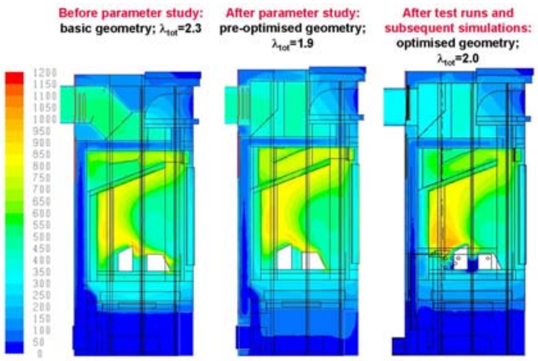

Figure 11: Selected simulation results: iso-surfaces of combustion and convective air temperature, flue gas and stove materials [°C] in the vertical symmetry plane of the stove

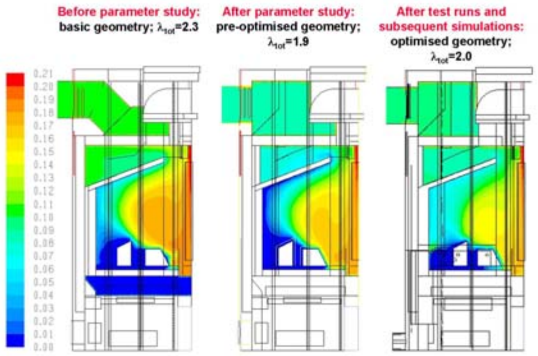

Figure 12: Selected results: iso-surface of O_2 concentrations [m^3 O_2/ m^3 flue gas w.b.] in the flue gas in the vertical symmetry plane of the stove

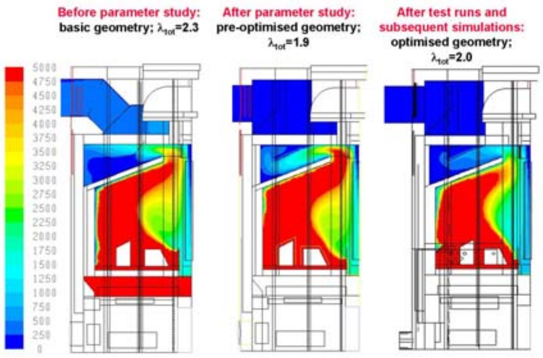

Figure 13: Selected results: iso-surfaces of CO concentrations [ppmv] in the flue gas in the vertical symmetry plane of the stove

Table IV: Test run results for the optimised geometry compared to corresponding benchmark values (related to dry flue gas and 13% O_2)

Parameter	Unit	Test run	Benchmark value
CO emissions	[mg/MJ]	429	750
OGC emissions	[mg/MJ]	15	50
Fine particulate emissions	[mg/MJ]	16	-
Dust emissions	[mg/MJ]	18	20

5 SUMMARY AND CONCLUSIONS

A new CFD based model for wood log fired stoves was developed and verified with measurements of combustion and convective air temperatures, flue gas and surface temperatures, mass loss of wood logs and flue gas composition in the chimney tube during several combustion batches performed with testing stoves.

The model was applied for the CFD aided development of a new wood log fired stove of the Austrian stove manufacturer HAAS+SOHN Ofentechnik GmbH. Starting from the CFD analysis of the basic concept of the stove, a parameter study concerning design and operation (amount of excess air) was performed in order to improve flue gas burnout, to lower CO and fine particulate emissions from incomplete combustion, as well as to increase the thermal efficiency of the stove. A prototype was developed based on the simulation results and test runs were performed with the prototype in a number of batches. Additionally, CFD simulations of the prototype were performed for selected test runs.

The results showed, that the CFD aided design of the stove led to considerably reduced CO emissions, OGC emissions, fine particulate emissions and dust emission (see Table IV) with an efficiency of the stove > 80%. This means that new technological standards have been set for natural draft wood log fired stoves with this development.

Concluding, the CFD based model for wood log fired stoves could be successfully validated and applied. It could be shown, that despite the complexity of the underlying processes, the model is well suited to perform realistic 3D simulations of wood log fired stoves and hence represents an efficient analysis and design tool.

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8 LOGO SPACE